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Experiments on the WavePiston, Wave Energy Converter

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***Abstract*— This paper analyses the performance of a new Wave Energy Converter (WEC) of the Oscillating Water Column type (OWC), named WavePiston. This near-shore floating device is composed of plates (i.e. energy collectors) sliding around a cylinder, that is placed perpendicular to the shore. Tests in the wave basin at Aalborg University allowed to investigate power production in the North Sea typical wave climate, with varying design parameters such as plate dimensions and their mutual distance. The power produced per meter by each collector is about the 5% of the available wave power. Experimental results and survivability considerations suggest that the WavePiston would be particularly suited for installations in milder seas. An example application is therefore presented in the Mediterranean Sea, off-shore the island of Sicily. In this case, each collector harvests the 10% of the available wave power. In order to allow the extension of the experimental dataset, an analytical model, based on mass-spring-damper system concept, is under development. The model is calibrated in order to represent the laboratory results for regular waves.**

***Keywords*— WavePiston, Wave Energy Converter (WEC), Oscillating Water Column (OWC), Power Performance, Experiments, Design Optimisation, Analytic Model.**

Nomenclature

H_s	significant wave height
T_p	peak period
L_w	wave length
P_w	incident wave power per meter
P_o	probability of occurrence
WS	wave state
d	distance between two subsequent collectors
a	model collector height
b	model collector width
$P_{R,ws}$	power produced per meter from the device in full scale for a particular wave state
P_p	mechanical power produced per energy collector from the device in full scale
P_{Ry}	yearly power produced per meter from the device in full scale
E_{Ry}	yearly energy produced per meter in full scale
η_{WS}	efficiency of the device for a wave state
η_a	yearly average efficiency of the device
m	mass of the analytical model
k	stiffness coefficient of the analytical model
c	damping coefficient of the analytical model

I. Introduction

In the last years, many wave energy converters (WECs) were proposed, first in the world of research, then in the commercial one. Different classifications of WECs do exist, according to their installation depth (off-shore, near-shore, in-shore), or to their orientation with respect to waves (attenuator, terminator, point-absorber).
The most common classification however is based on their working principle: overtopping devices (OTDs), wave activated bodies (WABs) and oscillating water columns (OWCs).

Usually an OWC is an on-shore structure, partially submerged and hollow below the water line. It is mainly constituted by a pressurized chamber where the waves can flow in and out. Waves run-up and run-down in turn compress and decompress the air column, that is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless to the airflow direction. The rotation of the Wells turbine is used to generate electricity.

The WavePiston is a new WEC belonging to the OWC category, invented by a Danish group including Martin Von Bülow and Kristian Glejbøl, from Copenhagen (as in [3]).

The WavePiston consists of multiple, floating, horizontal energy collectors placed perpendicularly to the sea bottom and attached to the same string.

Each energy collector is a large and thin plate, which can slide back and forth along a static string constituting by a long pipe compared to a typical wave length (see Figs 1 - 2). The pipe transports the pressurized sea-water to a collector point. At the collector point the pressurized sea-water can either power a turbine station or be used for desalination of the sea-water.

All the strings are positioned perpendicularly to the shore and they usually extend for at least two or three typical wave lengths (see Fig. 2).The WavePiston is an OWC system relying on the horizontal movement resulting from the oscillating water columns. In fact, the mutual movement between two subsequent plates is possible because, at the same instant, the phase angle of the propagating wave is different on the several plates.

Furthermore, for this reason, a large portion of the horizontal forces on the energy collectors will tend to cancel each other, reducing the summarized load on the structure in general, particularly on the mooring system

An additional benefit of the WavePiston configuration is that the floating energy collectors are located at the surface, where the wave movement is more intense.

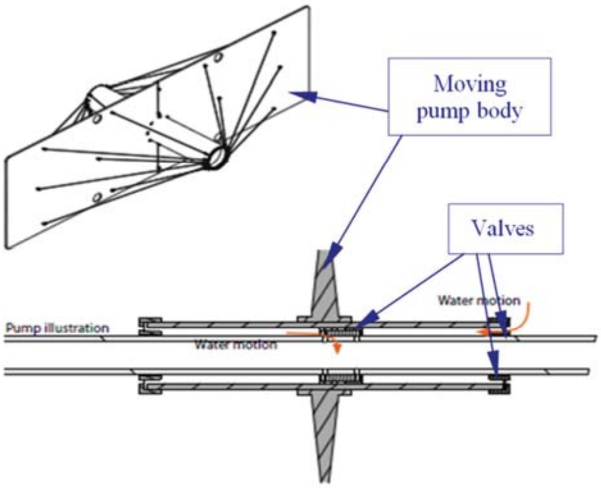


Fig. 1 - Possible WavePiston design. Due to the adaptability of the WavePiston principle, the exact design of the pumps can be tailored to the specific waters and location.

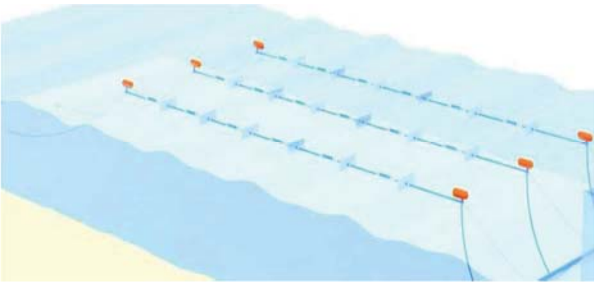


Fig. 2 - WavePiston future installation as a wave-farm. Note that for illustration purposes only 6 plates (modules) are drawn to each string. In a real WavePiston installation up to 50 collectors may be attached to ache string in order to get a full benefit.

The WavePiston should be built from prefabricated modules. Each module consists of an energy collector and a portion of the static structure (pipe). Building the system from modules makes it easy to transport, deploy and repair; in fact if a module fails, it will not compromise the entire system.

The WavePiston is designed for shallow coastal waters, so the necessary turbine and power conversion systems may be placed in the same onshore structure. This kind of installation allows a full control of the device also during storms and a significant reduction of the total installation costs, thanks also to the reduced cost of energy transfer to the shore.

Due to the oscillatory nature of the water movement along the WavePiston, the forces on the collectors will tend by large to cancel each other, as reported before. However residual forces, such as currents, winds, drift and forces induced by wave breaking, need to be compensated. The design of a proper mooring system for the device is therefore particularly relevant for a real installation.

Through an experimental investigation conducted at the University of Aalborg, in Denmark, it was possible to analyse the efficiency of this device and the feasibility of its application in different sea conditions.

Different shapes, mutual distances and numbers of energy collectors were analyzed, under a variety of wave attacks (different wave heights, wave periods and incident wave angles). Effects induced by changes of Power Take-Off loading were investigated as well.

A simplified analytical model is also proposed to analyse the collector movements and is applied to predict PTO rigidity for regular waves.

II. RESEARCH METHODOLOGY

A. *Brief description of the facility*

Experiments were carried out in February 2010, in the deep water wave basin of the Department of Civil Engineering, Water and Soil, at Aalborg University (DK).

The basin is 8.5m wide, 15.7m long, 1.5m deep (only in a small zone), and it is equipped with a snake-front piston type wave maker, with a total of ten actuators to simulate fully 3D sea waves.

Since the wave-maker is not provided with a fully system of absorption of the reflected waves, dissipation is performed on the sides of the tank through metallic breakwater and on the opposite side of the tank through an absorbing 1:4 beach made of gross gravel.

To control the paddle system, the AWASYS5 software developed by the University research group (as in [4]) is used.

B. *WavePiston Model*

To test the basic principle of the WavePiston system, i.e. the harvesting of energy from the horizontal movement of the waves, a model (in scale 1:30) of a WavePiston, having only four collector was created.

The down scale of a real system to particularly small scales may introduce large unknown measurement errors due to the fact that wave forces dramatically decrease whereas friction forces dramatically increase with scale.

Hence, a mere down-scale model of the WavePiston would have given false readings due to massive friction losses. The physical laboratory model was therefore modified with respect to the future WavePiston in order to overcome this problem. In order to get precise measurements as possible, the lab model was built with less friction effects as possible. The target was achieved by supporting the collectors with very light aluminium tubes suspended from a frame in pivot points 1.30m above the water surface (see Fig.3).

On the aluminium tubes, the floating collectors (each 0.5m wide and 0.1m high) are mounted such that vertical movement is allowed, whereas horizontal movement will force the tubes to rotate around the pivot point.

Since the distance between the collector and the pivot point is much larger than the expected collector movement, the (virtually) friction free arrangement constrains the collector to move in almost perfect horizontal paths, thus mimicking the movements of the plate in a real WavePiston arrangement.

A further significant benefit of choosing a frame is the easier precise measurements of force and collector displacements during a wave cycle.

Due to the semi-static nature of a supporting string in a real WavePiston system, it is believed that for a preliminary study the chosen laboratory arrangement gave exact performance results and at the same time removed the large source of error represented by the friction.

The Power Take-Off (PTO) of the lab consists of a friction wagon where the frictional force can be adjusted by adding or subtracting of weights.

By measurement of the force and of the displacement of the friction wagon it is possible to measure the work produced by the collector on the wagon. A load cell and a ultrasonic sensor (LVDT) were used to record the force and the displacement respectively (see Fig. 3).

It is reasonable that the full scale device does not present some lab limitations, such as the likely model rupture for the maximum displacement reached for the highest wave state, and wave diffraction effects induced by the fixed anchoring structure placed on the first front energy collector.

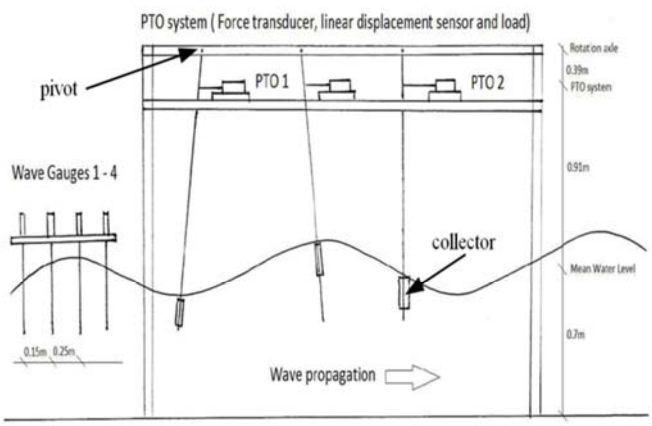


Fig. 3 - Configuration of the wave gauges and of the WavePiston in the laboratory with indication of the PTO systems (as in [8]).

C. Measurements

Wave height measurements were carried out by means of four resistive wave gauges located in front of the device (see the scheme in Fig. 3). The signals were recorded and analysed by the WaveLab3.33 software (as in [5]).

Measurements of the displacements of the device and of the forces were performed with a LVDT and a force transducer at each energy collector. The device velocity is derived from the difference of the displacement values in two successive sampling instants multiplied by the frequency of data acquisition. In some cases, due to non-fluent but jerkily movements of the collectors, the device displacement was not correctly measured and therefore velocity values are null.

Since the mechanical power is obtained as the measured force times the device velocity, the results and hence the device efficiency could plausibly be underestimated.

At the time of the experiments, the laboratory was also equipped with an additional computer, where a specific software "WavePiston.vi" based on the platform "National Instruments LabView 8.5" was dedicated to harvest the data from the lab PTO.

D. Test program

Aim of the experiments was the analysis of the device performance and specifically of its yearly energy production in typical North Sea conditions.

To find the optimal configuration of the device several tests were carried out (see table I) by changing:

– the wave condition, i.e. the wave type, regular (R-W) or irregular (IR-W) wave; the wave height (H_s); the wave period (T_p); the incident wave angle;
– the PTO loading values;
– the shapes (*a*,*b*), the mutual distances (*d)* and the number of the energy collectors.

The wave parameters, such as the H_s, and T_p are based on the standardized Danish North Sea, (as in [7]), at a scaling ratio of 1:30, on a hypothetical 20m deep location. In order to verify the device performance in the most general conditions, an additional study of different wave periods, wave heights and incident wave angles was also done.

All the irregular conditions tested were performed following the JONSWAP Spectrum, for a duration around 20 minutes.

A brief first phase, with energetic equivalent regular waves, was also performed, in this case each sampling had a duration of 3 minutes.

At the time of the experiment the water depth in the laboratory was maintained to a constant value of 0.7m.

TABLE I
DANISH WAVE STATES IN FULL SCALE (CALM 12.3%)

Wave State	H_s [m]	T_p [s]	P_w [kW/m]	P_o [%]
1	1.0	5.6	2.1	46.8
2	2.0	7.0	11.6	22.6
3	3.0	8.4	32.0	10.8
4	4.0	9.8	65.6	5.1
5	5.0	11.2	114.0	2.4

TABLE II
OVERVIEW OF THE TEST PROGRAM

	2 collectors		4 collectors	
	R-W	**IR-W**	**R-W**	**IR-W**
Choice of the Load range 0-5kg	x	x	-	x
Variation of wave period from 0.6s to1.8s	x	-	x	-
Variation of wave height from 0.03m to 0.11m	-	-	x	-
Variation of incident wave angle from 0° to 30°	-	-	x	x
Relative distance: 0.45m-0.55m-0.80m-2.40m	x	-	-	x
Different shapes	-	x	-	-

The load represents the friction effect of the full-scale WavePiston between the sliding movement of the plates and the pipe. The greater the load, the higher the resistance felt by the device to the movement and the lower the power production. The lower the load, the lower the force on the device and the lower the power production. It is therefore essential to find a compromise for PTO rigidity to derive the maximum power production.

The number of collectors and their distance are key issues, in fact they are strictly connected with the future full-scale installation. The collector geometrical dimensions are investigated, because the efficiency is highly depending on the area of the collectors that should be made as large as possible.

III. EXPERIMENTAL RESULTS

A. PTO rigidity

The identification of the best load is based on tests carried out for regular and irregular conditions.
In the lab, several weights (from 0 to 5 kg, with a step of 0.5kg when it was considered necessary) were used to represent the friction effect connected to the PTO rigidity.

The efficiency of each wave state is the key parameter in order to determinate the value of the best load. The efficiency η is therefore defined as the ratio between the power produced from the energy collector and the available wave power (P_w).

From the regular conditions (preliminarily carried out in 1:20 scale), the best weight on the friction wagon seems to be 2,5kg (see Fig. 4).

Since the efficiency trend is not linear and tends to decrease with increasing the wave height, a reduction of scale was studied (see Fig.5). Figure 5 shows that for the same test, the efficiency of the WavePiston is higher in scale 1:30 than in 1:20 scale, for this reason all the other tests were carried out in 1:30 scale.

However a more realistic result comes from the irregular conditions, which are more able to simulate the real sea.
Form irregular conditions, the ideal PTO loading, which corresponds to the highest amount of energy extractable from the device, is equal to 1.5kg (see Fig. 6), or 6.5N if one refers to the average standard deviation of the impressed force (in full-scale, this value would be 27kN). This value is therefore taken as the reference load for future design.

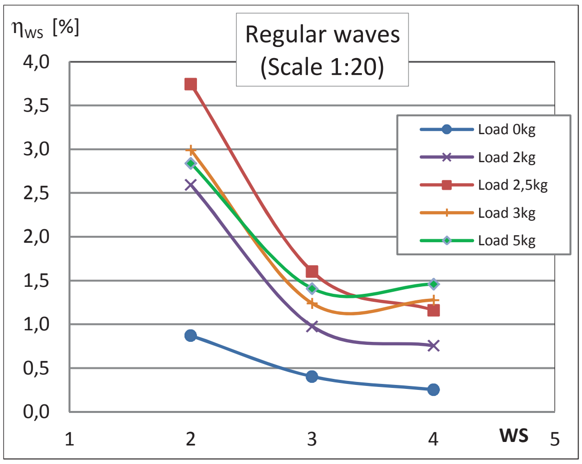


Fig. 4 - Efficiency (η_{WS}) trend for regular waves in scale 1:20. The best load value corresponds to 2.5kg. The plotted η_{WS} is measured at one energy collector.

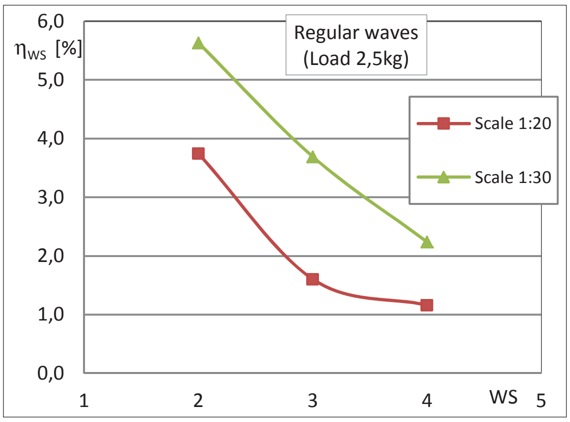


Fig. 5 - Efficiency (η_{WS}) trend for regular waves in scale 1:20 in red line with squares, and for regular waves in scale 1:30 in green line with triangles. The scale choice seems to be the 1:30 scale The plotted η_{WS} is measured at one energy collector, as before.

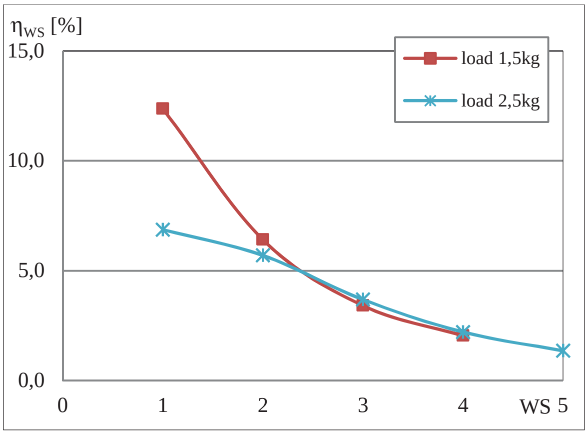


Fig. 6 - Efficiency (η_{WS}) trend with irregular waves. The best load value corresponds to 1.5kg, as perfect combination between high performance and stable standard deviation value. The plotted η_{WS} is measured at one energy collector as before.

B. Wave parameters

The variation of T_p from 0.6s to 1.8s entails a reduction of the efficiency η from 15.5% to 2.4% (see Fig. 7).
The lower the wave period the higher the η, and its trend is non-linear.

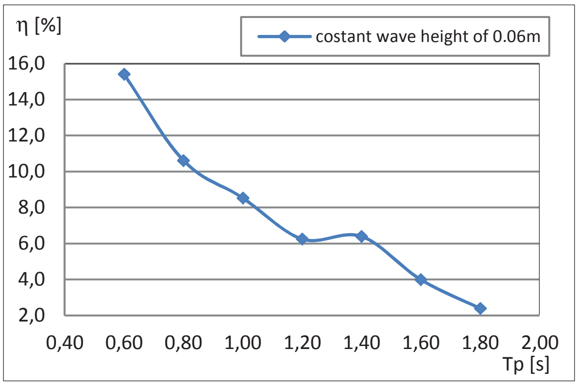


Fig. 7 - Efficiency (η_{WS}) trend with a variation of wave period. The efficiency decreases from 15.5% to 2.4% due to a variation of the wave period from 0.6s to 1.8s with a step of 0.2s. In this case, the plotted η_{WS} is measured as the average between the front and the rear energy collector.

The variation of H_s from 0.03m to 0.11m implies a decrease of η from 6% to 2.5%. As for T_p, the trend is non-linear and decreasing with increasing of the wave height.
The device globally results more dependent on T_p than on H_s.

The effect of the incident wave direction on η depends on the wave height (see Fig. 8).
The y-axis of Fig. 8 reports the value of the referenced efficiency ($\eta_{Referenced}$), which is the ratio between the efficiency derived for a particular wave obliquity and the efficiency related to the corresponding perpendicular incoming wave (direction 0°).
The greatest loss of η is for an incoming wave angle of 30°. It is approximately the 30% compared with the configuration where the device is in line with the incoming wave. This value can be considered not so significant because it occurs only for the WS n.2, where the mutual distance (d) between the plates was proportional to ½ of L_w. Therefore in the perspective of future installations, this result is interesting since it suggests that the WavePiston is suitable also for oblique waves, and specifically for limited changes of the wave angle (±30°) with respect to the device alignment, i.e. for instance in a bay.

C. Devices configuration

1) Number and Distance of the energy collectors

In the first WavePiston configuration there were only two energy collectors at a mutual distance of 2.40m, whereas in the second one there were four energy collectors placed at a mutual distance of 0.45m, 0.55m and then 0.80m. Experiments were performed for both configurations only with irregular waves.

In the multi-collector configuration the reduction of η is less than the 20% with respect to the two-collector case. So the rear plates do not experience a dramatic wave energy damping.
This aspect is essential in future installations where the device will be composed by a number of energy collectors. Furthermore, the experiments (see Fig. 9) show the greatest loss of η for a medium value of distance (0.55m), hence for the full-scale it is recommended a configuration where the distance between the plates is close to $n \cdot L_w/4$, where n is an odd positive integer. This result can be explained considering the reflection effects in nodes and anti-nodes between the collectors.

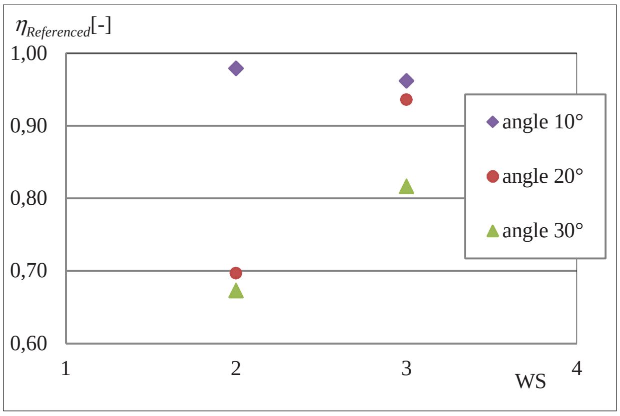


Fig. 8 - Influence of the incident wave angle variation on the efficiency tested with irregular waves. Coordinates represent the percentage loss of efficiency with respect to waves parallel to the device, i.e. perpendicular to the shore.

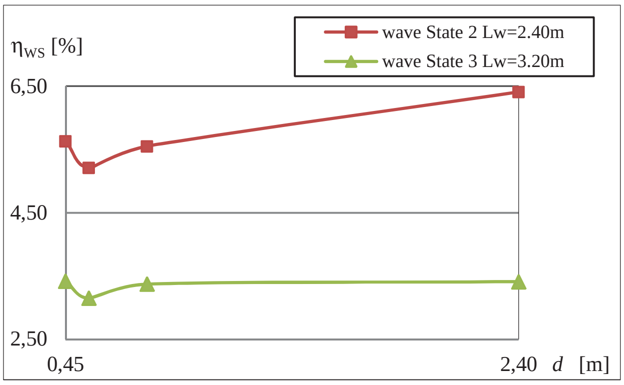


Fig. 9 - Influence of the mutual distance from the collectors on η, tested with irregular waves. The configuration studied are 0.45m-0.55m-0.80m-2.40m. The high efficiency loss is for a mutual distance of 0.55m, whereas for the closer configuration there is not a significant efficiency loss, so the back plate does not feel a relevant wave energy damping effect.

2) Dimension of the energy collectors

In the reference "target" configuration, each energy collector is 0.50m wide (see the *b*-dimension in Fig. 10) and 0.10m high (see the *a*-dimension in Fig. 10) as declared before.
The following other configurations were also examined:

- 0.38m x 0.10m;
- 0.38m x 0.13m;
- 0.38m x 0.07m.

The comparisons done are:

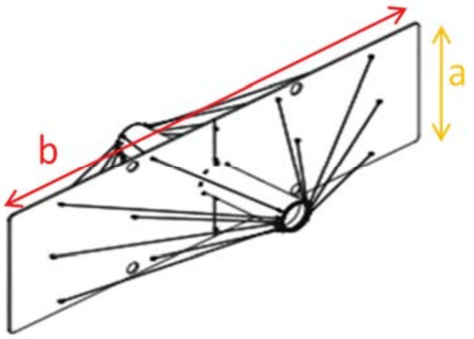
- same height *a* of 0.10m and different widths;
- same width *b* of 0.38m and different heights.

Experiments were made only with irregular waves and two collectors.

The lower the width, the greater the efficiency; however the peak efficiency increases of about the 20% for the width 0.38m with respect to the 0.50m width, both for the same height a=0.10m, (see Fig. 10).

Instead, the greater the height, the greater the efficiency, and the efficiency might raise up to three times.

The greatest increase of peak efficiency occurs for the collector 0.38m x 0.13m, with respect to the collector 0.38m x 0.10m (see Fig. 11).



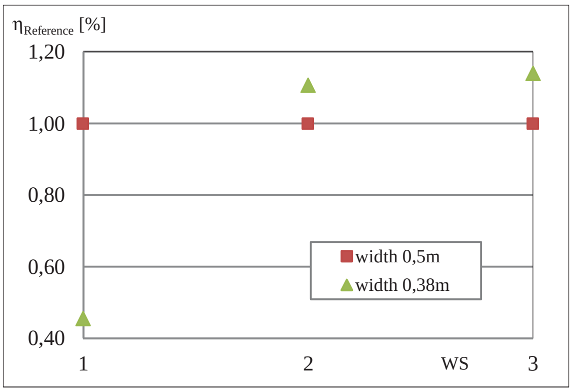


Fig. 10 - Efficiency variation due to the different collector width of 0.38-0.50m keeping constant the height of 0.10m. The greatest efficiency increase is around 20% for the plate of sizes 0.38m x 0.10m, with respect to the plate 0.50m x 0.10m.

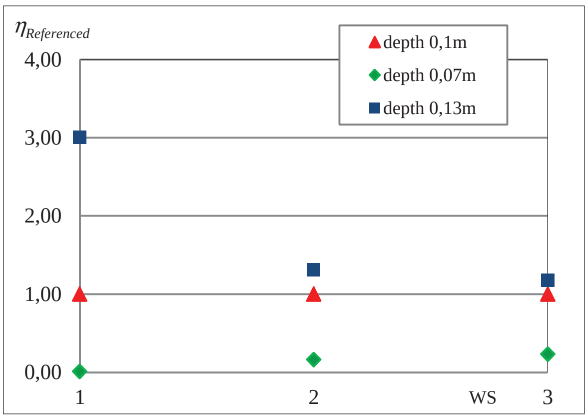


Fig. 11 - Efficiency variation due to the different collector heights of 0.07-0.10-0.13m keeping constant the width of 0.38m. The greatest efficiency increase is around 300% for the plate of sizes 0.38m x 0.13m, with respect to the plate 0.38m x 0.10m.

D. *Power production*

The efficiency of the WavePiston decreases in a non-linear way from the lower to the higher wave states, with a trend similar to other OWCs (as in [10]).

Fig. 12 shows the efficiency trend for the full-scale device combined with an indication of the wave power.

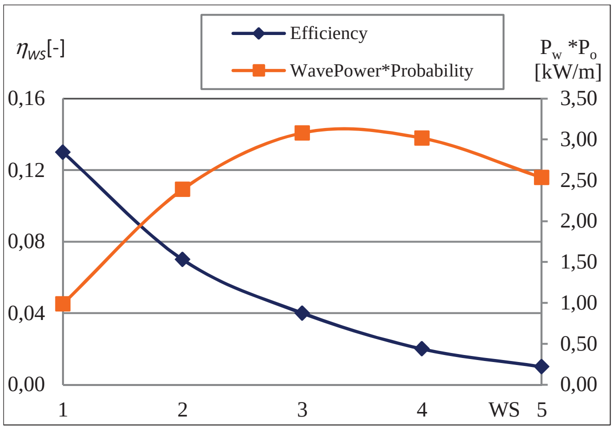


Fig. 12 - WavePiston efficiency in the North Sea conditions (blue solid line with diamonds) and available wave power multiplied by the probability of occurrence (orange solid line with squares).

For the Danish part of the North Sea, with a yearly available average wave power (P_w) of 12.00 kW/m, the WavePiston can generate a yearly power ($P_{R,y}$) of about 0.55 kW/m, corresponding to a yearly energy production per meter ($E_{R,y}$) of 4.24 MWh/y/m.

The most important results are summarized for the full-scale device in table III.

The produced mechanical power per collector (P_p) is simply obtainable by multiplying the produced power per meter ($P_{R,WS}$) for the total width of the collector in full-scale.

TABLE III
SUMMARIZING PERFORMANCE OF THE FULL-SCALE DEVICE IN THE NORTH-SEA INSTALLATION

Wave State	H_s [m]	T_p [sec]	P_w [kW/m]	P_o [%]	η_{ws} [-]	$P_{R,WS}$ [kW/m]
1	1.0	5.6	2.1	46.8	0.13	0.28
2	2.0	7.0	11.6	22.6	0.07	0.74
3	3.0	8.4	32.0	10.8	0.04	1.14
4	4.0	9.8	65.6	5.1	0.02	1.19
5	5.0	11.2	114.0	2.4	0.01	1.06
	Yearly values		12.0	-	0.08	0.55

IV. APPLICATION OF THE WAVEPISTON IN ITALY

The number of mechanical components subjected to wave load and the higher efficiency for mild Seas suggests a possible WavePiston installation in the Mediterranean Sea.

The WavePiston is supposed to be installed off shore the Sicilian coast as a good compromise between wave energy available and an appropriate knowledge of wave climate (see Fig. 13).

The wave climate was reconstructed through the RON data acquired in Mazara del Vallo, 37°38'43.19" N and 12°34'57" E. RON is the acronym for National Wavemeter Network (*Rete Ondametrica Nazionale*), and it is active since July 1989 (as in [2]). Each RON buoy is placed on deep water, it is able to follow the surface motion and is monitored by means of a satellite system. Each buoy sends the data to a sampling stations every three hours for a period of 30 minutes.

The RON data have been analysed considering the operating limit state instead than ultimate limit state. The wave probability of occurrence during the typical annual climate was examined for deriving the PTO and the typical annual power production.

The representative wave states were derived by associating to each class of wave height the wave period obtained as a weighted average based on the occurrence of all the wave periods observed for that class (see table IV).

The experimental results can be used as reference results in every location characterized by the same wave states or by similar wave states. The first step of the analysis is therefore the comparison between the Danish Wave States and the Sicilian Wave States. Since the wave states trends are similar (see Fig. 14), it is appropriate to exploit the Danish results to the Italian case.

Fig. 13 - Location of Mazara del Vallo, island of Sicily, Italy.

TABLE IV
SICILIAN (ITALY) WAVE STATES IN REAL SCALE (CALM 2.7%)

Wave State	H_s [m]	T_p [s]	P_w [kW/m]	P_o [%]
1	0.25	5.5	0.13	26.8
2	0.75	5.8	1.23	33.3
3	1.25	6.6	3.91	19.2
4	1.75	7.2	8.37	10.7
5	2.25	7.9	15.05	4.9
6	2.75	8.6	24.41	2.4

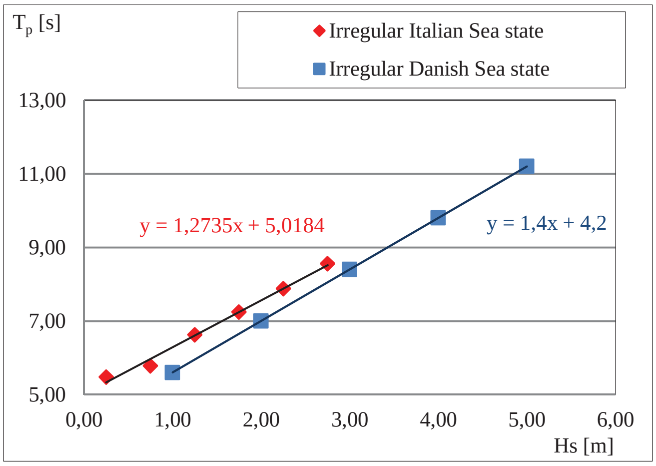


Fig. 14 - Irregular Danish wave state (blue solid line with squares) and Irregular Sicilian wave state (red solid line with diamonds).

The Italian WSs are however characterized by lower values of H_s and T_p; in order to extrapolate the experimental results for milder conditions, it is made the assumption of keeping constant the efficiency trend.

The WavePiston efficiency for a Danish installation has a tendency curve of exponential type (see Fig. 15), described by:

$$y = 0.2535 \cdot e^{-0.638 \cdot x} \qquad (1)$$

where x is the known H_s in meter, and y is the desired η.
Based on the values of H_s in the study site and on the corresponding η derived from equation (1), the wave power P_w, the yearly efficiency η_a and the yearly energy production ($E_{R,y}$) can be directly estimated based on the following equations (see Fig. 16 and table V):

$$\eta_a = \sum_{WS=1}^{6} \eta_{ws} \cdot P_{o,ws} \qquad (2)$$

$$P_{Ry} = \sum_{WS=1}^{6} P_{R,WS} = \sum_{WS=1}^{6} \eta_{ws} \cdot P_{o,ws} \quad [\text{kW/m}] \qquad (3)$$

$$E_{Ry} = P_{Ry} \cdot 365 \cdot 24 \quad [\text{kWh}/(\text{y} \cdot \text{m})] \qquad (4)$$

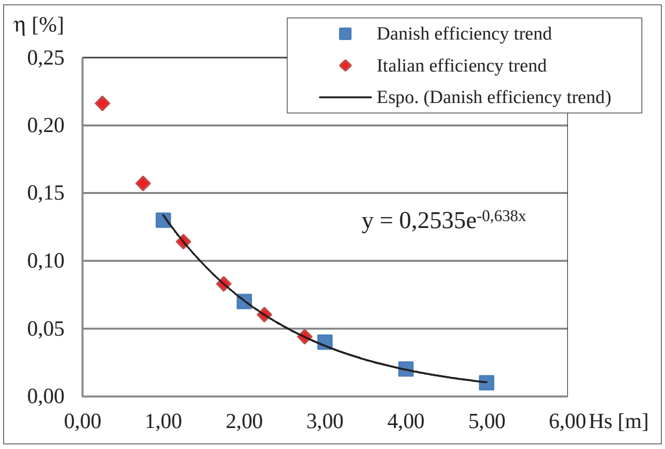


Fig. 15 - Danish efficiency trend for the WavePiston power performance carried out through the laboratory results (in the blues squares) and corresponding efficiency in the Italian installation (in the red diamonds).

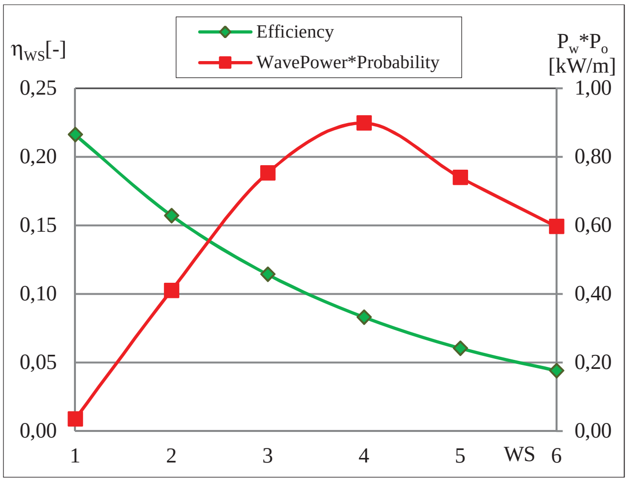


Fig. 16 - WavePiston efficiency in Sicily, off-shore Mazara del Vallo (green solid line with diamonds) and available wave power multiplied by the probability of occurrence (red solid line with squares).

TABLE V
SUMMARIZING PERFORMANCE IN AN ITALIAN INSTALLATION

Wave State	H_s [m]	T_p [sec]	P_w [kW/m]	P_o [%]	η_{ws} [-]	$P_{R,WS}$ [kW/m]
1	0.25	5.5	0.13	26.8	0.22	0.03
2	0.75	5.8	1.23	33.3	0.16	0.19
3	1.25	6.6	3.91	19.2	0.11	0.47
4	1.75	7.2	8.37	10.7	0.08	0.69
5	2.25	7.9	15.05	4.9	0.06	0.91
6	2.75	8.6	24.41	2.4	0.04	1.07
	Yearly values		3.43	-	0.15	0.30

Table V shows the output energy of the WavePiston for the installation off-shore Mazara del Vallo, where the yearly available average wave power (P_w) is 3.43 kW/m (about 1/4 of the Danish yearly available average wave power).

The device can generate a yearly power ($P_{R,y}$) of about 0.30 kW/m, corresponding to a yearly energy production per meter ($E_{R,y}$) of 2.66 MWh/y/m.

V. Analytical Model

To identify the power performance of the WavePiston in a generic location regardless the laboratory results, an analytic model should be developed. An attempt is presented below.

The first phase of the model is a simulation for the research of the best load, as done in the laboratory period. It is supposed that by changing the weight on the PTO system the energy collector has a different movement freedom. The analytical model is therefore based on the simple mass – spring – damper concept.

Each energy collector (i.e. the mass (m)) is assumed to behave as a rigid body with a single degree of freedom, where:

– the spring stiffness coefficient (k) represents the real spring placed on the plate of the PTO system that limits the movements of the collector;
– the damping value (c) represents the different movement freedom of the collector ;
– the external force ($f(t)$) is explainable with the Morison equation.

The following equation is solved:

$$m\ddot{x} + c\dot{x} + kx = f(t) \qquad (5)$$

being $x=x(t)$ the displacement of the collector during the simulation.

The model requires many input values and some assumptions, synthesized in the following list.

1. The whole mass of the device is assumed to be concentrated only in the energy collector, regardless structural elements such as the static pipe.
2. A particular stiffness value (k) is hypothesized, i.e. k = 100 N/m, hence to move the collector of 1cm, a force of 1N (1N=100g) is necessary. This value may be changed, depending on more accurate force-displacement measures.
3. The damping coefficient (c) varies from 0 to 100 Ns/m. A small damping value can be compared to a small weight on the PTO system plate. In fact a small damping value implies a large range for the displacement, hence for the velocity, but at the same time a low value of the impressed force, because the collector does not make resistance to the flow motion. Thus, it is expected that a mean value for the damping coefficient would lead to the best performance.
4. The model is run for a particular wave state for each simulation. For this step, regular waves were used in order to simulate the laboratory phase with the same wave typology. The wave is usually described by an harmonic signal, consequently the displacement and the force on the collector are also represented by harmonic signals.
5. Regarding the external forces, the system is simplified as a fixed body in an oscillating flow.

Through the *ad hoc* Matlab script (as in [6], [9]), the trends of the displacements (consequently the velocity of the collector) and the power connected to the damping value variation are obtained.

Fig. 17 shows different displacements of the collector depending on different damping values for a selected wave condition. The blue points represent the situation without damping, while the black points are for the maximum damping value under exam. As predictable, the displacements decrease from the situation without damping (that represents the free movement) to the situation with the maximum damping (corresponding to the maximum resistance). Furthermore, the displacement trend is harmonic as the one of the external force.

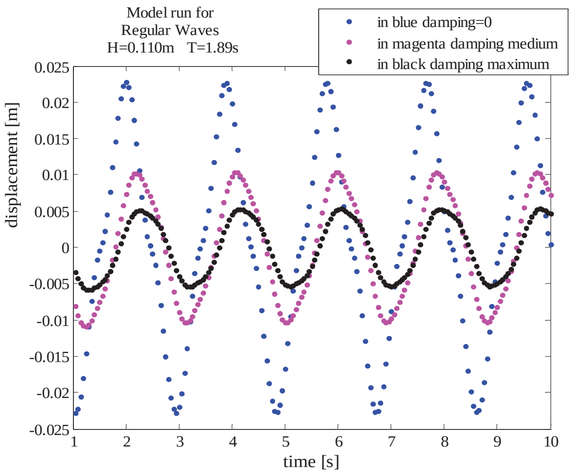


Fig. 17 - Different collector displacements due to the variation of the damping values from 0 to 100 Ns/m for the same wave test. In the Figure there are only the first 10 sec to better perceive the collector displacement trend.

Fig. 18 shows a decrease in the velocity standard deviation from the situation “free movement and zero damping” to the situation of "maximum damping". On the opposite, the standard deviation of the force increases with an increase of the damping value. Since velocity and force have opposite trends, the best damping value is selected based on the curve of the generated power.

In all the tested conditions, the model shows the optimal damping value *c* to be in the range 20 Ns/m-30 Ns/m (see Fig. 19). This result can be compared to the load 2.5kg, found in the experimental study for the best PTO rigidity.

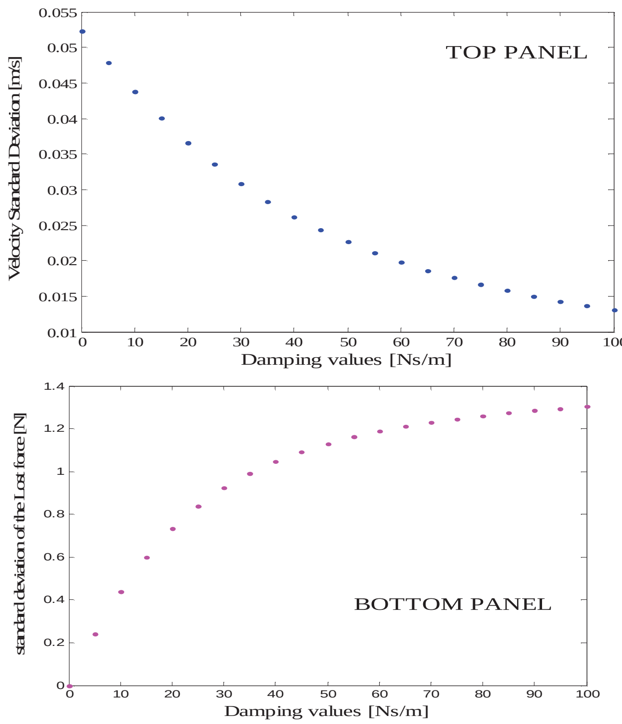


Fig. 18 - Different standard deviation of the collector velocity in the top panel (blue filled in points) and different standard deviation of the impressed force in the bottom panel (magenta filled in points) related to different damping values for a single wave test.

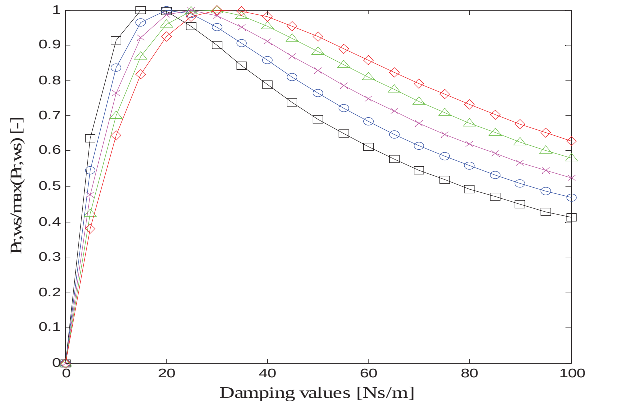


Fig. 19 - The graph shows an optimal damping range from 20 Ns/m to 30 Ns/m for all the wave states. The y-axis reports the power per meter produced for a particular wave state non-dimensionalized with its maximum. The results are shown in different colours and with different markers depending on the wave state: WS=1, black solid line with squares; WS=2, blue solid line with circles; WS=3, magenta solid line with crosses; WS=4, green solid line with triangles; WS=5, red solid line with diamonds.

The recorded movement of the collector, in a laboratory test, is described below for regular waves (see Fig. 20) in order to provide an attempt of a comparison with the harmonic movement assumed in the model.

Figure 20 shows the movement recorded in the laboratory for the same wave state analyzed in the model and shown in Fig. 17. The motion of the collector is similar to an harmonic signal, but the oscillation range and the average value of the displacement randomly varies in time.

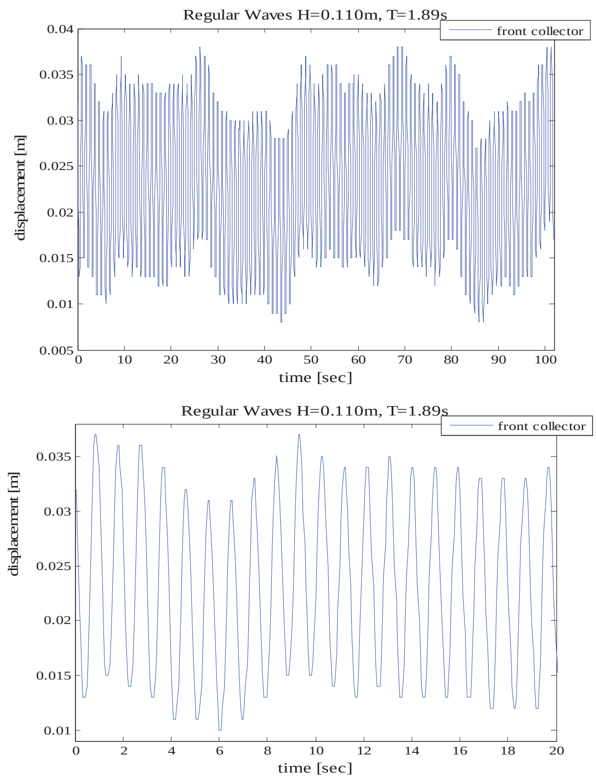


Fig. 20 - The graphs show the recorded movement, in the lab, for the front collector for the test characterized by regular waves with H=0.110m and T=1.89s. In the bottom panel there is a zoom for the first 20s.

This trend highlights the discontinuity of the collector displacement, that it was sometimes jerkily as already reported. This aspect suggests an accurate future design to ensure a continuous collector movement without reaching the full range.

Since the basic equation (5) and its assumptions are so far very simple, it is out of the scope of this contribution to propose a direct comparison between the computed and the laboratory measured efficiency. In fact, the analytical model uses a damping dissipation, whereas in the lab there was a friction dissipation. Therefore the differences between the analytical model and the lab conditions are well known, and in the second phase of the model (not completed yet) the basic equation is changed to include the friction effect (F) and not the damping, as follows:

$$m\ddot{x} + kx = f(t) - F \qquad (6)$$

In the research world there are not so many wave test Research Centres, so it is essential the study of a valid analytical model to forecast the performance of a general WEC.

The model representing the WavePiston should be further developed to consider:

- the real friction dissipation;
- the mechanical and structural limitations in order to identify the right size of the collector;
- an adaptable PTO to the wave states, in particular the way used to realize and control it;
- the real displacement of every collector connected to the floating mooring, and so the real future mooring system design;
- the possibility to install a WavePiston wave-farm;
- an economical investigation.

VI. Conclusions

The WavePiston is able to convert wave energy into useful mechanical energy, which then, through further mechanical and electrical systems, can be converted into electricity.

As an OWC, the WavePiston has the advantage of a near-shore location, that in turns leads to:

- an easy access for operation and maintenance work;
- lower energy transmission costs;

and similarly has the disadvantage of the lower available wave power compared to the off-shore zone.

Since it is a floating structure, the WavePiston however does not share with OWCs the problem of the high visual impact.

In case of the North Sea conditions, the WavePiston potential power production from each collector is the 5% of the available wave power.

Experiments provided useful indications for design optimisation. In fact the device efficiency increases significantly with increasing the height of the collectors. The suggested mutual distance is as small as possible. A configuration where the mutual distance is close to $n \cdot L_w/4$, where n is an odd positive integer, is recommended.

A future study regarding a farm of WavePiston is suggested, because based on experiments with multi-collectors, installations with multi-devices should not interfere one another and increase wave energy harvesting capacity.

Furthermore indications regard the optimal wave conditions are afforded from the experimental results. In fact, the WavePiston efficiency increases with decreasing the wave period or the wave height.

Based on design analysis, the WavePiston installation is recommended in milder sea states, where the rupture risk due to storms is minimal and also the hydraulic efficiency is higher.

Starting from the experimental results, an application to a milder sea condition was performed. The chosen location is Mazara del Vallo, off-shore the Sicilian coast, Italy. In the Italian installation with a yearly available average wave power (P_w) of 3.43 kW/m (about 1/4 of the Danish yearly available average wave power), each energy collector would be able to generate a $P_{R,y}$ of 0.30 kW/m that corresponds to the 10% of the available wave energy.

An analytical model is under development with the ultimate scope of predicting the WavePiston efficiency at any installation site.

So far the first step of the modelling is proposed, consisting in a mass – spring – damper system able to reproduce the experimental research of the PTO best load in regular wave states.

Acknowledgment

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